Prediction of Alfalfa Forage Yield Loss due to Freezing Injury: I. Model Development and Sensitivity Analysis

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Introduction

Freezing injury causes extensive dry matter (DM) yield loss in alfalfa (*Medicago sativa* L.) exposed to cold winters in North America. Existing simulation models for alfalfa either do not account for freezing injury effects or do not differentiate cultivars for their varying response to freezing stress and subsequent effects on forage production. Alfalfa models must simulate freezing injury effects in a cumulative way so that forage yield can be accurately predicted over multiple years of the same crop. This is particularly important when models are used to evaluate cropping systems or management alternatives in relation to farm profitability. The objective of this project was to incorporate cultivar specific effects of freezing injury on forage yield into an existing alfalfa model (ALSIM 1, Level 2) to predict yield over the life of an alfalfa crop. The new model was titled ALFACOLD, an acronym to mean 'ALFAlfa model for yield prediction in COLD climates.' Model structure and sensitivity of predicted yield to changes in model parameters are presented in this paper. Model validation is presented in a companion paper.

Methods

Model development. Numerical functions of cold tolerance, fall dormancy and freezing injury were developed from data in the literature, and integrated with the growth processes in the ALSIM model. A schematic representation of the ALFACOLD model is shown in Fig. 1. If cold tolerance, fall dormancy, freezing injury and population components shown in Fig. 1 are excluded, the resulting diagram would represent the ALSIM model.

ALFACOLD model simulates growth as a function of air temperature, solar radiation, soil moisture, and plant density. It predicts DM growth in leaf, stem and buds on a daily basis. Material available for top growth and storage (MATS) is equivalent to photosynthate after respiration has been subtracted. Material in MATS is partitioned daily into leaves (LEAF), stems (STEM) or total non-structural carbohydrates (TNC) in the crown and root tissue. The TNC are utilized in the formation of buds (BUDS) that elongate into new leaves and stems during regrowth. While DM partitioning pathways are the same in ALSIM and ALFACOLD, rate equations defining the amount of material flow are different because of the additional processes of fall dormancy and freezing injury in ALFACOLD. Effect of fall dormancy on growth is modeled as a function of cultivar's fall growth score (FGS). Plant death due to freezing injury is modeled as a function of cultivar's potential for cold tolerance, and magnitude and duration of freezing soil temperature in the crown region. Effect of snow cover on soil temperature is estimated from air temperature and snow depth. Soil water (AW) movement and evapo-transpiration are modeled to compute water stress factor to account for the effects of limited water supply on crop growth.

ALFACOLD model simulates plant death and consequent yield loss due to freezing injury only. While freezing injury may be a dominant cause of winterkill in cold regions, other factors such as ice sheeting, poor soil aeration or low soil potassium can add significantly to winter injury when alfalfa is grown on poorly drained or infertile soils. The model assumes adequate drainage and soil fertility. The model ignores the effects of pests and diseases on plant kill. The model does not simulate growth during a seeding year.

Input data needed are: (1) daily solar radiation (W m^{-2}), maximum and minimum air temperature (°C), and precipitation (mm); (2) latitude (degrees); (3) harvest dates; (4) cultivar's Fall Growth Score (FGS); (5) initial plant density (plants m^{-2}); and (6) maximum plant available water in the root zone (mm). Plant density and FGS are not required to run ALSIM. The computer code, documentation, and sample data files are available upon request from the primary author.

Sensitivity analysis. Changes in ALFACOLD predictions of forage yield to a ± 25% change in the

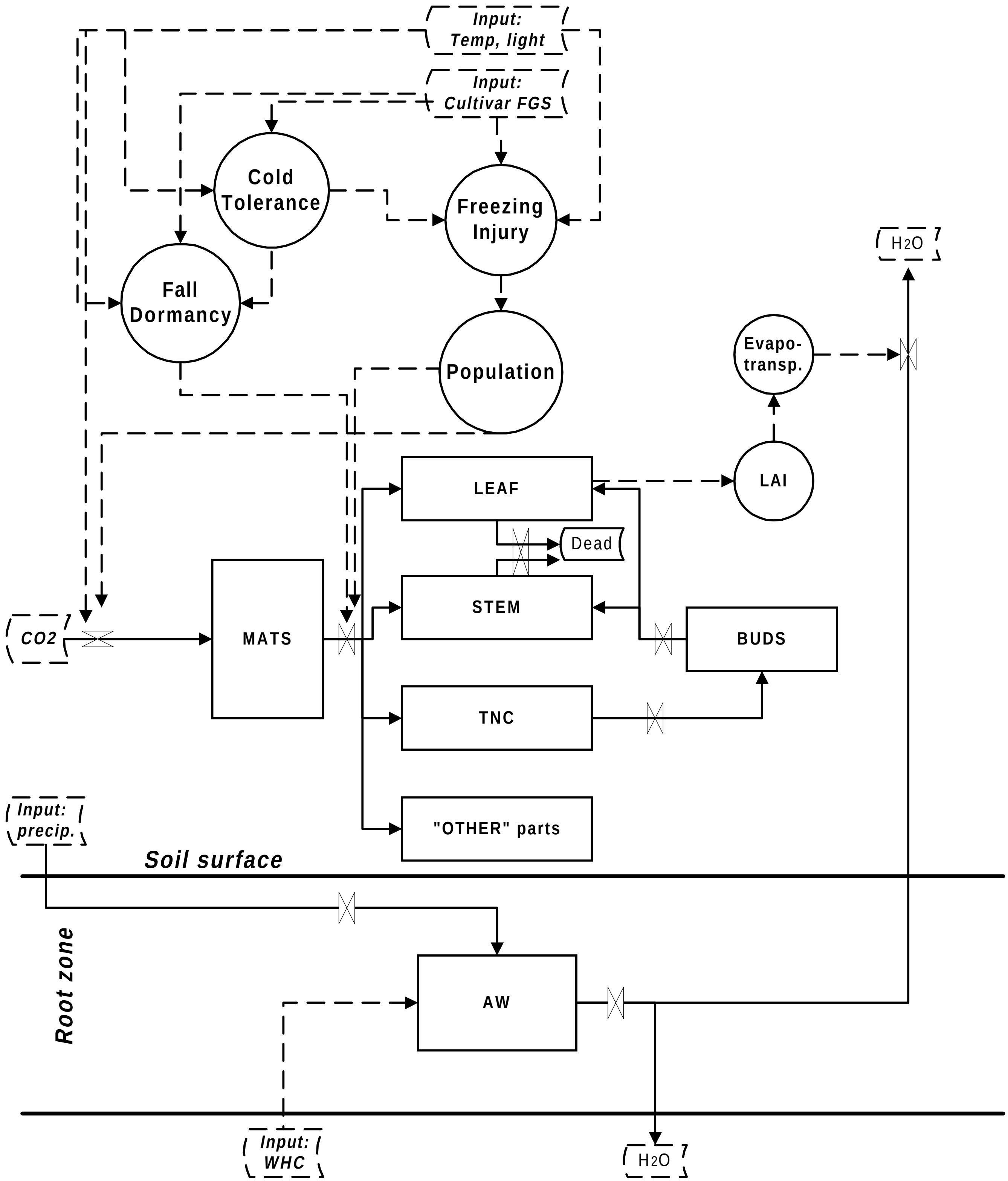

Figure 1. A simplified schematic representation of the alfalfa model, ALFACOLD. (Boxes represent model states; circles for auxiliary variables, processes or components; solid lines for material flow; dashed lines for information flow; valves for rate functions; dashed-line boxes for input/output. Acronyms are defined in the text.)

Table 1. Sensitivity Index (SI, Eq. 1) for forage DM yield to a ±25% change in selected model parameters for three different cultivars of FGS of 2, 3, and 4 during three production years: PY1, PY2, and PY3. (An absolute SI value greater than 1 indicates that the model is very sensitive to the particular change.)

				Sensitivity Index (SI)					
				Negative Change (-25%)			Positive Change (+25%)		
Variable definition	Acronym	Scenario†	Reference‡ value	PY1§	PY2	PY3	PY1	PY2	PY3
Potential crop death coefficient (d^{-1})	PDFMX	CV2	0.109	0.0	-0.05	-0.05	0.0	-0.05	-0.05
		CV3	0.121	0.0	-0.10	-0.10	0.0	-0.10	-0.10
		CV4	0.133	-0.0	-0.70	-0.80	-0.0	-1.30	-1.40
Potential rate of cold hardening (°C d^{-1})	CHRMX	CV2	0.184	0.05	0.30	0.35	-0.0	0.10	0.15
		CV3	0.162	2.45	3.85	3.95	-0.05	0.25	0.30
		CV4	0.139	4.00	4.00	4.00	0.05	1.00	1.10
Potential rate of dehardening (°C d^{-1})	CDRMX	CV2	0.820	0.20	0.20	0.30	0.05	0.05	0.05
		CV3	0.795	0.20	0.05	0.10	0.05	0.0	0.05
		CV4	0.770	0.0	-0.15	0.60	-0.0	-0.20	-0.20
Lowest temperature tolerance (°C)	CTMX	CV2	-22.4	-0.05	-0.05	-0.05	-0.0	0.0	-0.15
		CV3	-20.4	-0.05	0.0	-0.05	-0.0	0.0	-0.05
		CV4	-18.4	-0.20	1.35	1.40	0.0	0.0	0.0
Snow (mm)	SNOD	CV2	dlyinp¶	0.0	0.0	0.0	0.0	0.0	0.0
		CV3	dlyinp	0.05	0.0	0.0	0.05	0.0	0.0
		CV4	dlyinp	0.25	1.70	1.70	0.10	0.55	0.60
Initial plant density (plants m^{-2})	POP_{init}	#CV2	160	0.25	0.30	0.35	0.10	0.30	0.35
		CV3	160	0.20	0.70	0.80	0.15	0.30	0.30
		CV4	160	0.20	1.80	1.80	0.20	0.80	0.90

Eq. 1: SI = (DY/Y)/ (DP/P), where Y represented model predicted forage DM yield (kg ha^{-1} yr^{-1}), and P represented the value of a model parameter or input variable.

† Three scenarios, coded as CV2, CV3, and CV4, correspond to 3 different cultivars with FGS of 2, 3, and 4, respectively, during 3 production years.

‡ Reference value for each parameter was extracted from functions developed based on data in the literature. Each reference value was subjected to a ± 25% change.

§ PY1, PY2 and PY3 are three consecutive production years after a seeding year in Arlington, WI. Measured weather data were used as model input.

¶ Daily snow fall data (SNOD) were subjected to a ± 25% change.

Initial plant density at the start of a simulation was subjected to a ± 25% change.

newly added parameters (Table 1) were determined to test the ability of the model to respond to varying intensities of freezing injury in cultivars of contrasting FGS. Three production years of a 4-year crop grown in Arlington, WI spanned 1991-93. These years were selected because crop reports indicated substantial variation in winter injury during this period. Three different scenarios were produced (coded as CV2, CV3 and CV4) that corresponded to forage production in three different cultivars of FGS 2, 3 and 4, respectively. Most cultivars grown in this region fall in the range of 2 to 4 FGS. Each simulation was started on 1 March 1991 and ended on 31 October 1993. The simulated crop was harvested in 4 cuts on May 26, June 27, July 29 and August 27 in all three years.

Results and Discussion

Sensitivity of predicted yield to changes in the selected parameters under the three scenarios simulated for Arlington, WI is presented in Table 1. Model parameters associated with sensitivity index (SI) absolute values greater than 1.0 were considered very sensitive while SI values less than 0.5 indicated low sensitivity of model output to changes in parameter value or to variation in input data due to potential measurement errors.

Except for the crop death coefficient (PDFMX, d^{-1}), ALFACOLD was generally more sensitive to a decrease (negative change) in parameter value than to a corresponding increase. Sensitivity generally increased with crop age as plant density decreased due to winterkill following repeated exposure to winter seasons. Predicted forage yield was influenced more by a cultivar's rate of cold hardening (CHRMX, °C d^{-1}) and lowest temperature tolerance (CTT, °C) than by the rate of dehardening (CDRMX, °C d^{-1}). High values of SI for rate of cold hardening suggest that the model needs carefully measured experimental data for this parameter. Error in estimating snow cover had minor effect on predicted yield in hardy cultivars but had a greater impact on yield predicted for the less hardy cultivars. Need for good plant density in the first production year was revealed during the second and third production years as plant population declined due to winterkill following repeated exposure to cold winter seasons.

Conclusion

(1) The ALFACOLD model predicted forage yield on a daily basis while accounting for the cumulative effect of freezing injury on yield over multiple years of the same crop. (2) The model parameters added showed sensitivity to freezing injury as expected. (3) Sensitivity analysis indicated that cold hardening rate and lowest temperature tolerance influenced yield more than the rate of dehardening in spring. (4) ALFACOLD can be incorporated into whole farm simulators, such as the DAFOSYM model, to predict forage yield daily while accounting for the effects of winter injury on forage production, thus influencing farm economics.